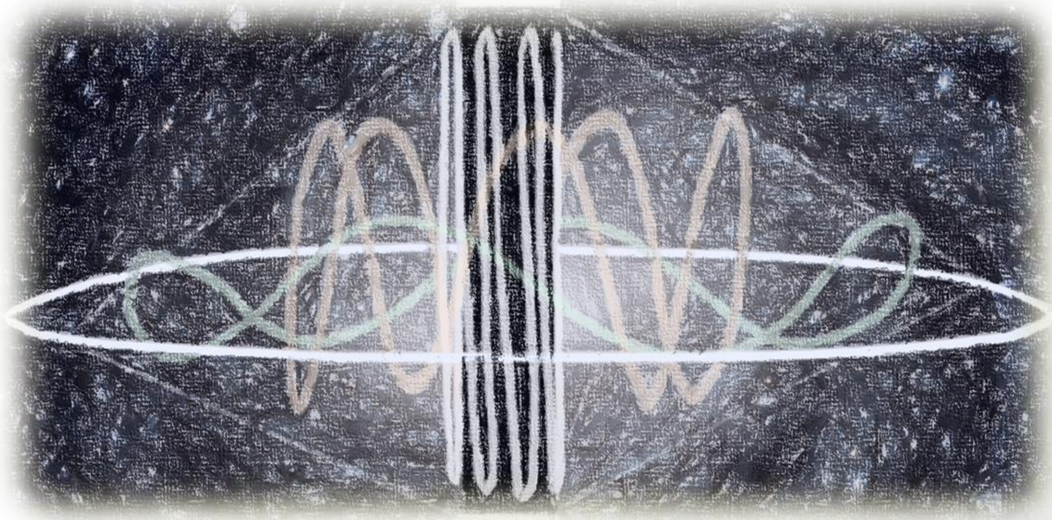
High-Temperature Superconductors (HTSs) as Electromagnetic Deployment and Support Structures in Spacecraft



PI: Prof. David W. Miller
Gwendolyn V. Gettliffe
MIT Space Systems Lab

NIAC Spring Symposium
March 28, 2012

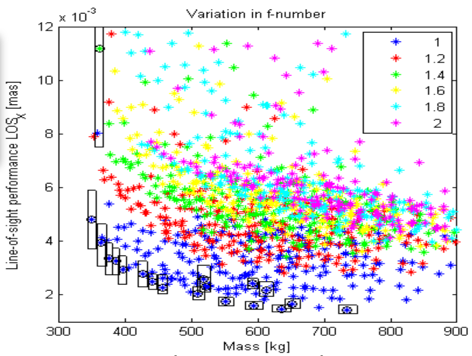
MIT Space Systems Laboratory

From Vision to Orbit: Designing Systems for Space

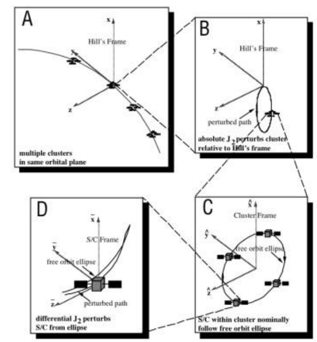
Mission Statement: Using comprehensive mission analysis, identify key enabling technologies and mature them through terrestrial and on-orbit testing.

Space Technology Maturation

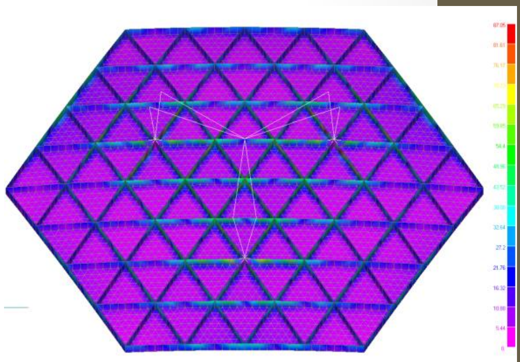
Mission Analysis



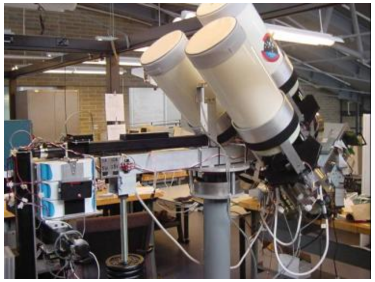
Trade space studies



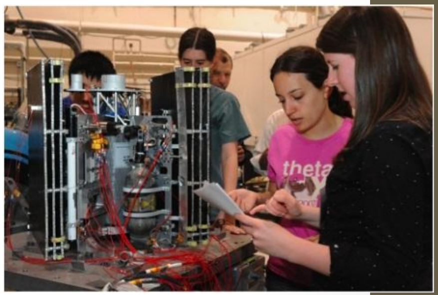
Orbit/constellation design


Active mirror design

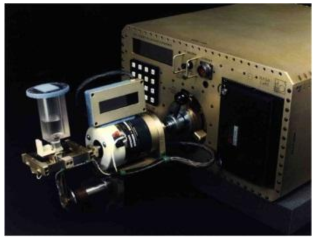
Terrestrial Technology Development


Interferometric imaging

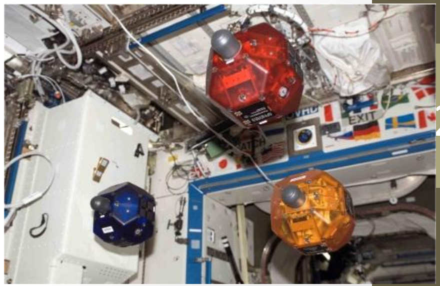

Electromagnetic propulsion


Student-built spacecraft

On-Orbit Validation

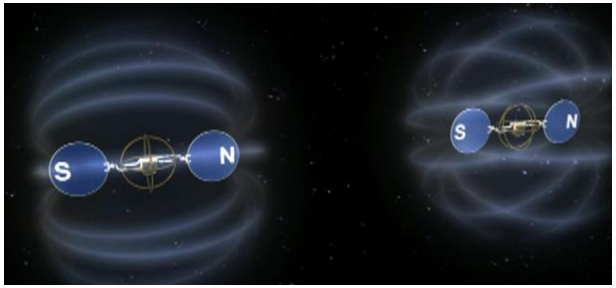

MODE experiment (Shuttle)

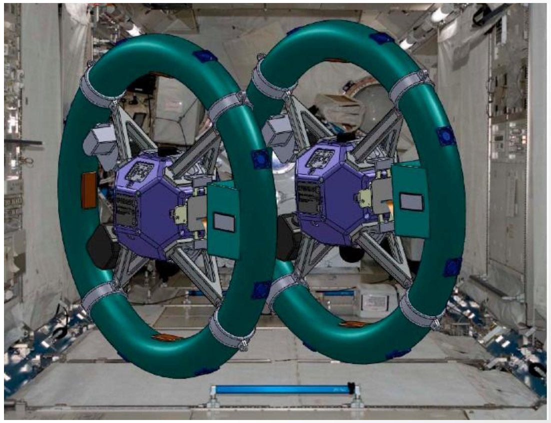

MACE experiment (Shuttle & ISS)


SPHERES facility (ISS)

Electromagnetic Formation Flight (EMFF)

- Subject of 2002 NIAC study
- Basic Concept
  - Provide actuation in relative degrees of freedom for formation flight systems using electromagnetic forces/torques and reaction wheels
- Motivation
  - Station-keeping for distributed satellite systems
  - Replacement of consumables (thrusters)
  - Eliminate thruster plumes
  - Enable high ΔV formation flying missions
- Implementation
  - Create a steerable electromagnetic dipole using three orthogonal electromagnetic coils made of superconducting wire.
  - De-couple torques by using reaction wheels
  - Demonstrated in 3DOF in lab, using cryogenic heat pipe
  - **Next step: ISS demonstration (RINGS)**

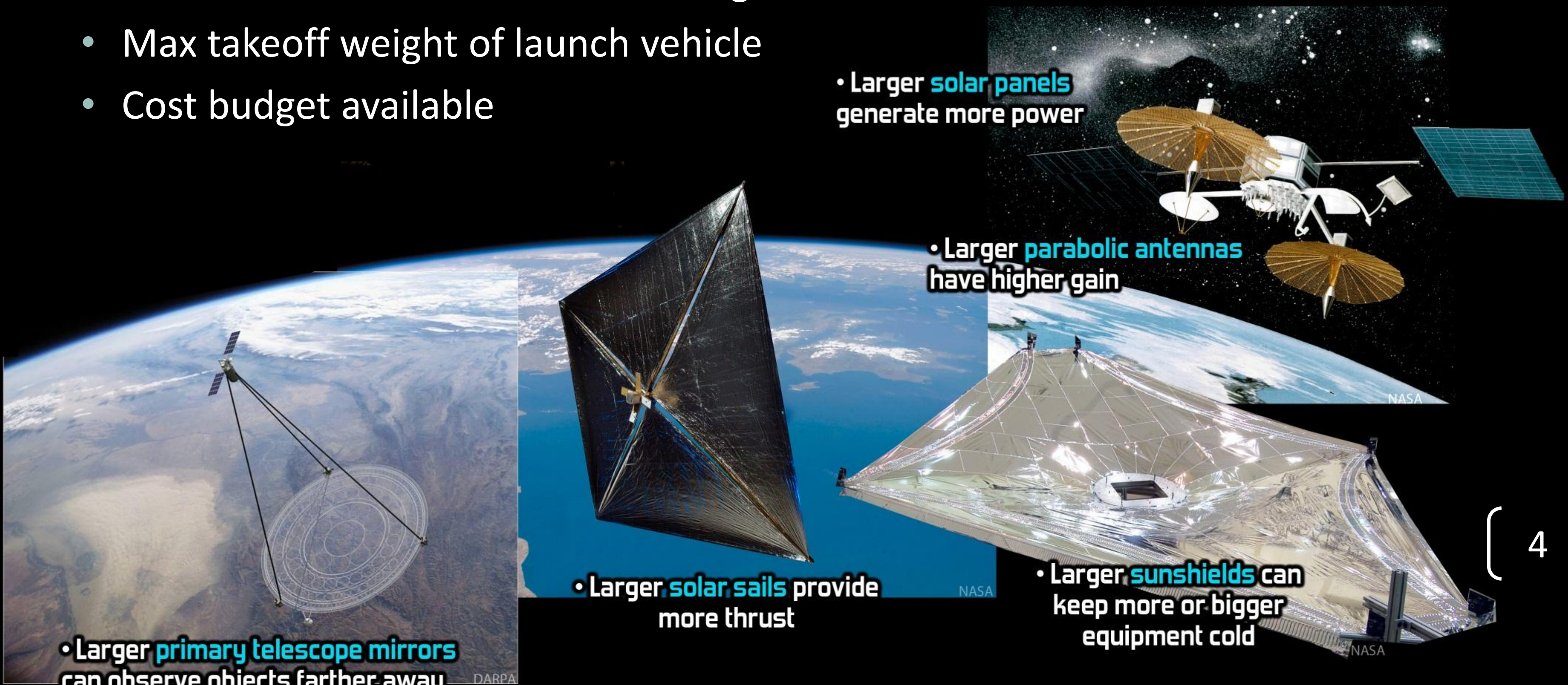




Credit: Sedwick (UMD)

Background

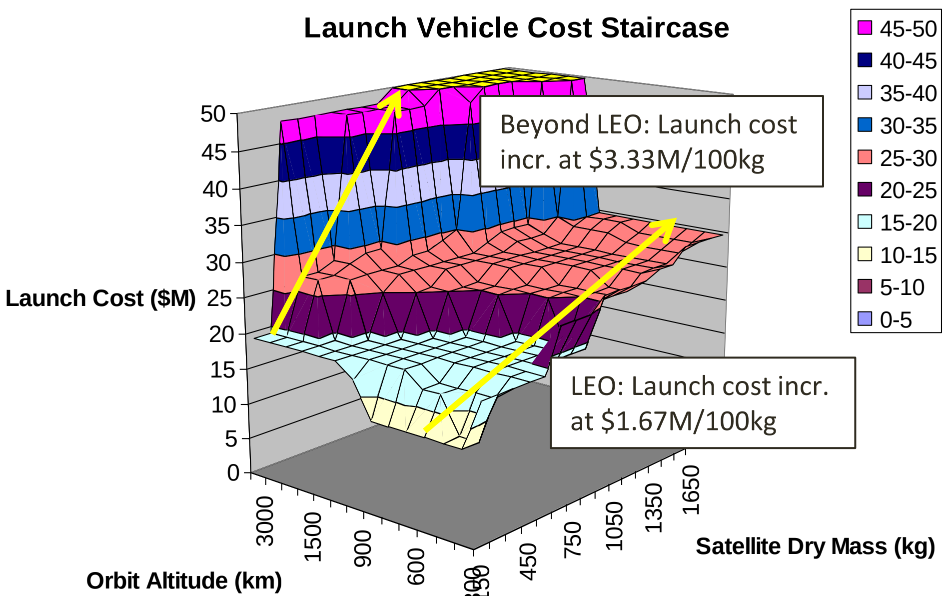
- Many space structures have performance benefits at larger sizes
- However, spacecraft size is limited by a number of factors, including but not limited to:
  - Dimensions of launch vehicle fairing
  - Max takeoff weight of launch vehicle
  - Cost budget available



Structures: Massive and Costly

Top 4 Most Massive Subsystems Avg, from SME-SMAD [25] Tbl A-1:

Subsystem (% of Dry Mass)	No Prop (%)	LEO Prop (%)	High Earth (%)	Planetary (%)
Payload	41%	31%	32%	15%
Struct/Mech	**20%**	**27%**	**24%**	**25%**
Power	19%	21%	17%	21%
Attitude D&C	8%	6%	6%	6%



Credit: Bearden (2001) [2]

Structural components are 2nd largest avg. fraction of spacecraft dry mass - translates to greater launch vehicle costs

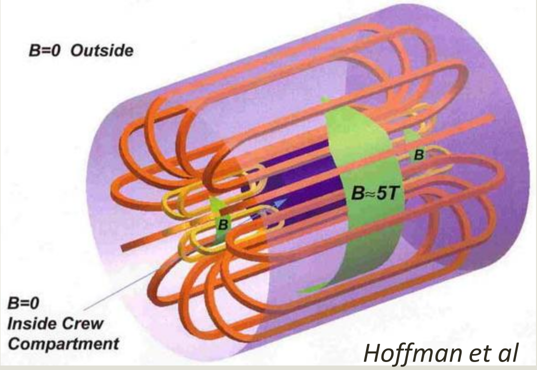
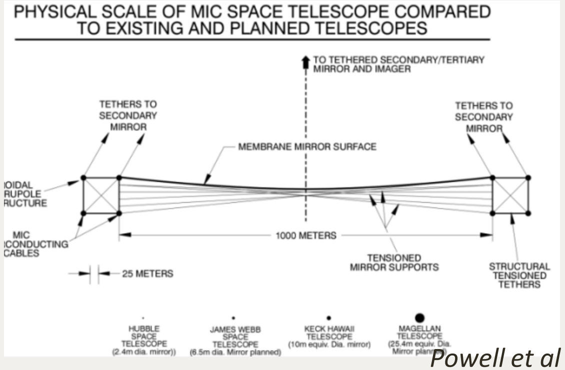
Reduction of structural mass is a worthwhile investment applicable to all spacecraft, especially those leaving Earth's orbit

But we still want the performance benefits of large structures!

Electromagnetic forces could support larger structures for less mass…

Superconductors and NIAC

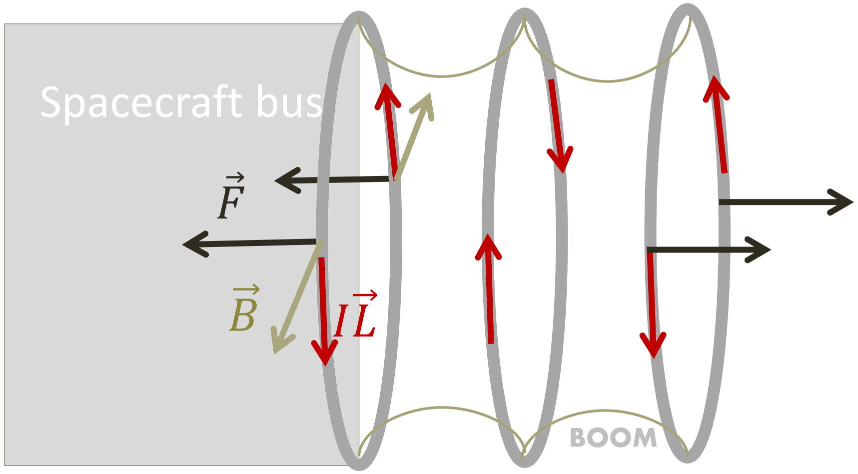
- Previous NIAC studies have touched on space applications of superconductors and magnetic fields, including:

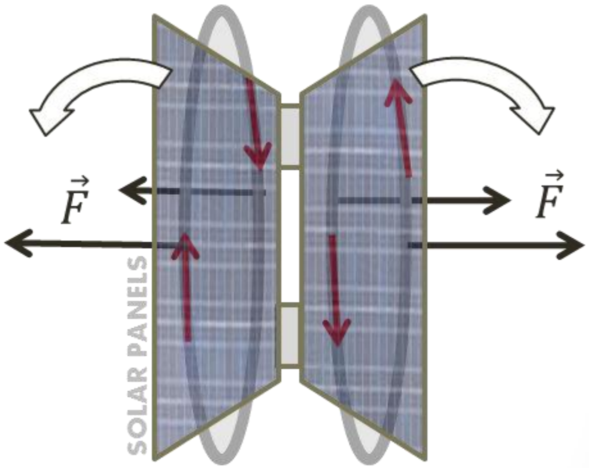
Principal Investigator	Subject
Miller/Sedwick (2002)	Electromagnetic formation flight
Zubrin (1999)	Magnetically tensioned solar sails (“magsails”)
Hoffman (2004), Westover (2011)	Radiation protection for astronauts  *Hoffman et al*
Powell (2005)  *Powell et al*	Conceptual studies of magnetically-expanded high-temperature superconductor (HTS) cables for applications like: • LEO propulsion using Earth’s mag. field • Energy storage for lunar bases • Large telescopes w/ perimeter tensioning

Study Questions

TECH

1. Can we use electromagnetic forces generated by and acting between **high-temperature superconductor (HTS) current-carrying coils** to move, unfold, and support parts of a spacecraft from its stowed position?





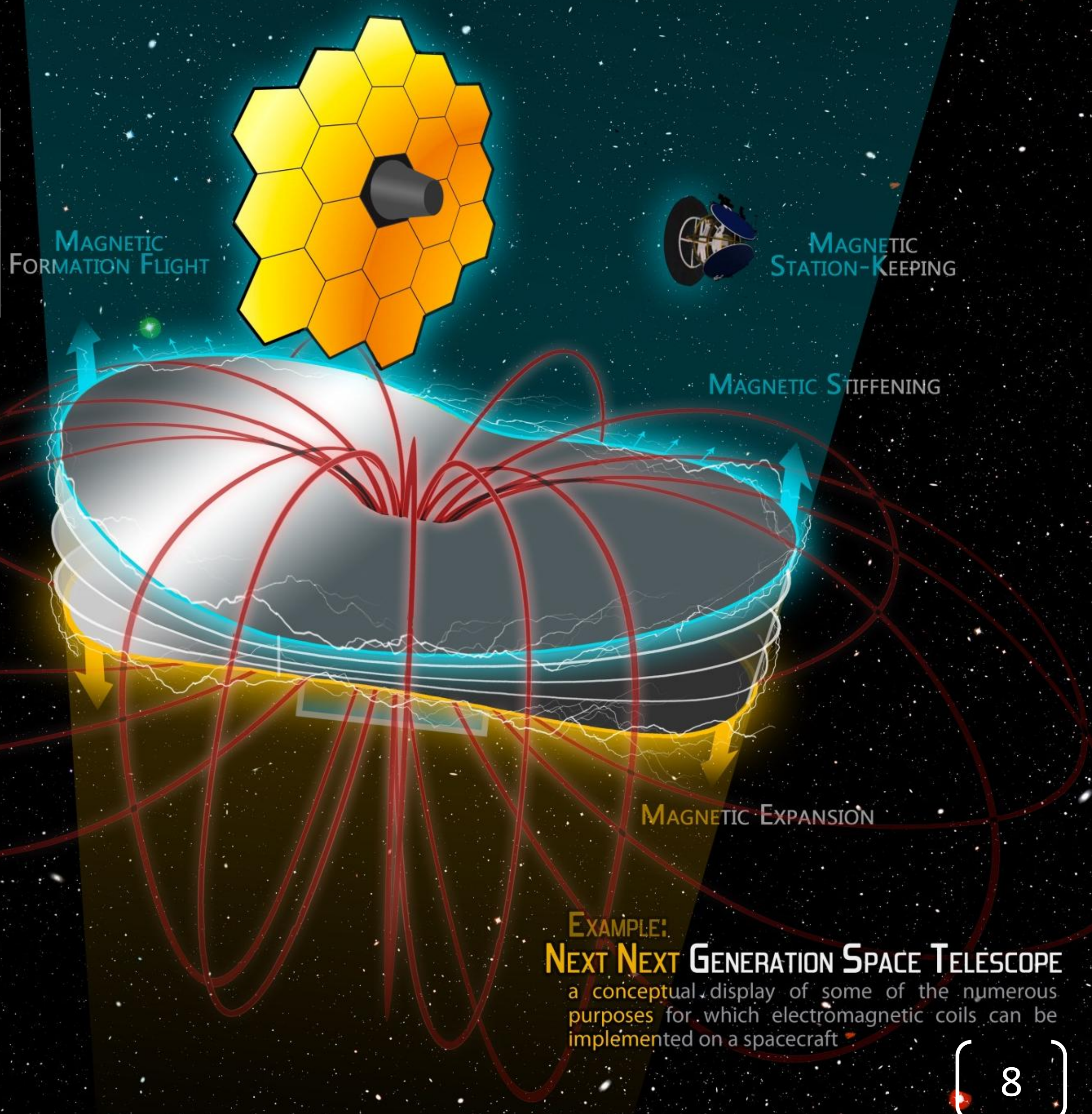
2. For what operations does this technology represent an improvement over existing or in-development options?
3. What new mission capabilities does this technology enable?

SYSTEMS

Vision: Next Next Generation Telescope

Many potential functions and advantages of electromagnets on spacecraft, including:

- Wireless power and data transfer
- Electromagnetic formation flight and positioning
- No obscuration from 2nd mirror assembly
- Unfolding from stowed position
- Staged deployment and element upgrades/replacement
- Magnetic stiffening and tensioning
- Reduced # of deployments
- Attitude control & momentum trading
- Dynamic and thermal isolation
- Membrane mirror shaping



Previous Contributions to Vision

Many potential functions and advantages of electromagnets on spacecraft, including:

Function	Work by
Wireless power and data transfer	***Work by:*** Fisher, Soljačić (WiTricity) [9], Sedwick (RINGS) [20]
Electromagnetic formation flight and positioning; No obscuration from 2nd mirror assembly	***Work by:*** Kwon [11,12], Kong [8], Schweighart [18], Miller, Sedwick (EMFF), Sakaguchi (µEMFF) [17], Peck (flux pinning) [22], Sedwick (RINGS) [20]
Unfolding from stowed position; Staged deployment and element upgrades/replacement	***Work by:*** Zubrin (Magsail) [26], Powell (MIC Structures) [15], Benford (Microwave spin) [4]
Magnetic stiffening and tensioning; Reduced # of deployments	The scope of our study – deployment-oriented
Attitude control & momentum trading; Dynamic and thermal isolation	***Work by:*** Pedreiro (Disturbance Free Payload) [21]
Membrane mirror shaping	***Work by:*** Palisoc (holographic) [13], Ritter (photonic) [16], Bekey (scanning electron/shape memory) [3], Patrick [14], Stamper [23]

Motivation

TECH PUSH

- High-temperature superconductor performance improvements
- Electromagnetic formation flight demonstrated
  - Many structural functions exist that can be performed magnetically

MISSION PULL

Large flagship spacecraft like JWST need structures that are:

Credit: NASA

- Light
- Simple
- Large
- Thermally isolated
- Vibration isolated
- Reparable w/out servicing

Electromagnetic Structures and Mechanisms

Study Objectives/Progress

TECHNOLOGY

Define magnetically performable functions & design vector

Develop usable model of coil physics

Design example structures

SYSTEMS

Derive quantitative & qualitative impacts of HTS structures

Discuss architecture trade

Describe emergent capabilities

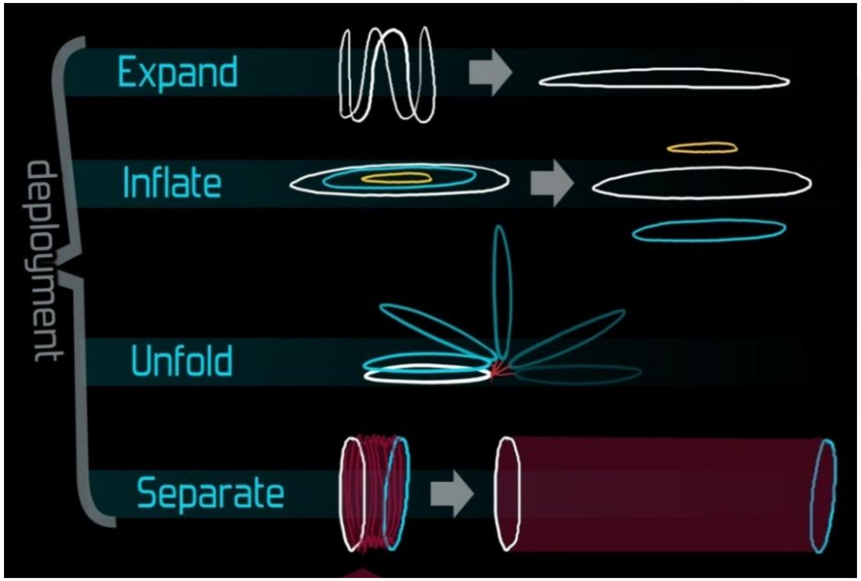
Study Objectives/Progress

TECHNOLOGY

Define magnetically performable functions & design vector

Develop usable model of coil physics

Design example structures



HTS DESIGN VECTOR

- -Power req'd per duty type (W)
- -Type of thermal control
- -Current (A)
- -AC or DC current?
- -Resistance of circuitry (Ω)
- -Magnetic field strength (G)
- -Deployment time (s)
- -Deployment steps (#)
- -Type of physical constraints
- -Type of HTS
- -Quantity of coils (#)
- -Quantity of turns (#)
- -Length of HTS cable used (m)
- -Size ratio (stowed/deployed)
- -Change in separation (m)

- Involve one or more coils repelling or attracting one another
- Depend upon boundary conditions to differentiate the performed functions
- Design vector identifies design variables that will eventually factor into trades

Study Objectives/Progress

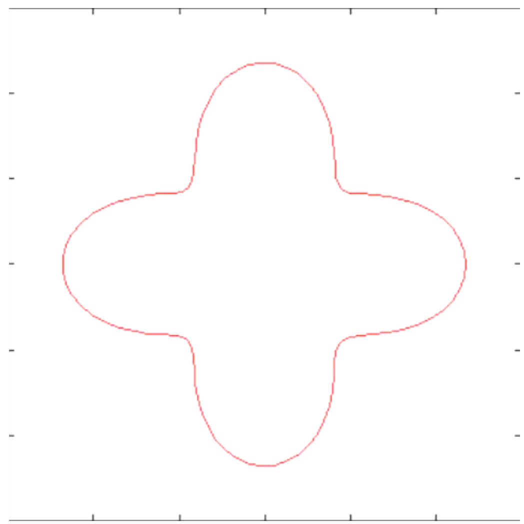
TECHNOLOGY

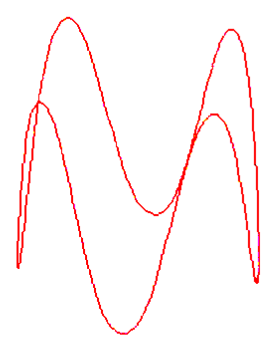
Define magnetically performable functions & design vector

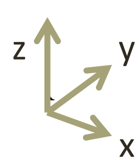
Develop usable model of coil physics

Design example structures

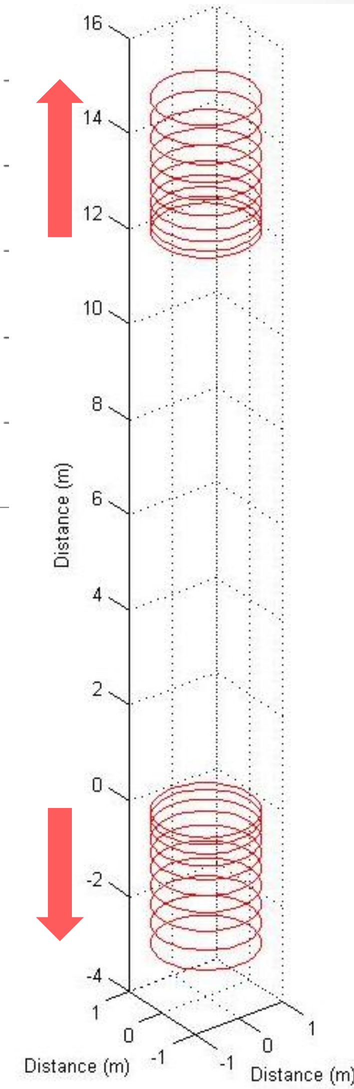
- Numerical appx of Biot-Savart Law
- One coil modeled as flexible but non-elastic, with mass
- Two coils modeled with mass, matches far-field analytical sol'n (valid at >10x coil diameter separation)
- Still need to incorporate:
  - Elasticity
  - Bending stiffness







Coil separation in space w/ time



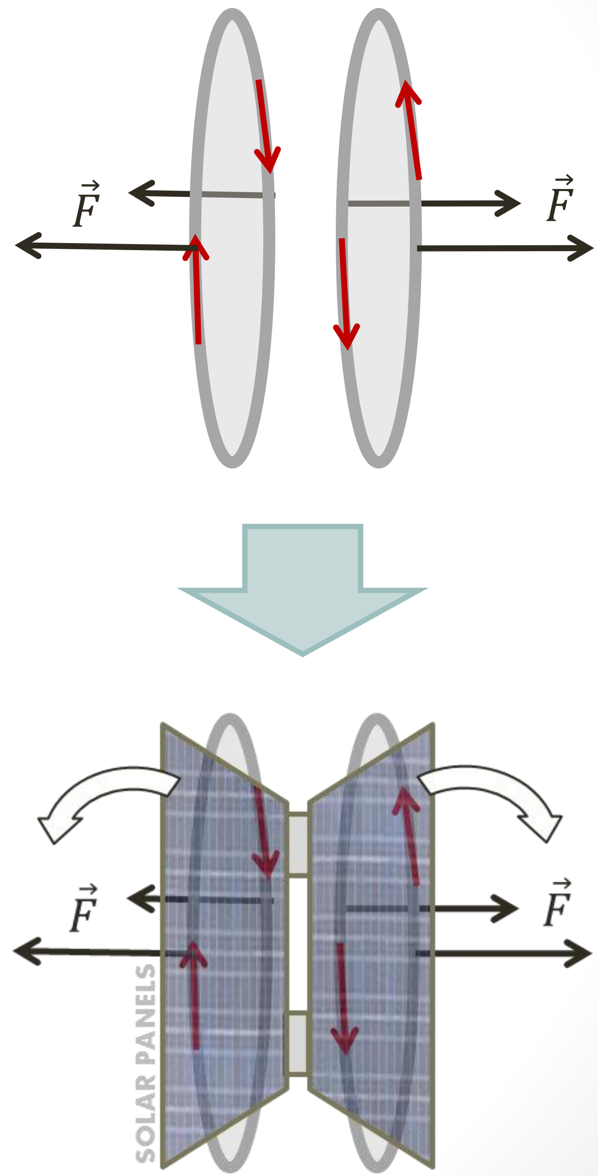
Study Objectives/Progress

TECHNOLOGY

Define magnetically performable functions & design vector

Develop usable model of coil physics

Design example structures



Example structures take the defined deployment and support configuration models and apply

constraints (boundary conditions) and ***additional mass***

to better simulate actual structure deployment

Study Objectives/Methods

Subsystem or process	Example impacts of HTS structure choice
Avionics/ Comm	Potential electromagnetic interference
Thermal	Additional thermal control required, little or no conduction
ADCS	Current regulation needed, Earth's magnetic field, additional momentum trading possible
Optical Path	Risks to position accuracy and disturbance control
Structures	Reduction of mass, vibration isolation, increased compaction ratio, enables reconfiguration
Propulsion (if EMFF)	No propellant required, eliminates thruster plumes
Power	Additional power draw
Testing	Difficult in 1g

SYSTEMS

Derive quantitative & qualitative impacts of HTS structures

Discuss architecture trade

Describe emergent capabilities

- Selection of HTS structural design impacts every subsystem
- Extent to which (and whether the impact is net positive or net negative) is determined by the priorities of the program
- Overarching HTS effects are:
  - Good for structures
  - Not so good for power and thermal

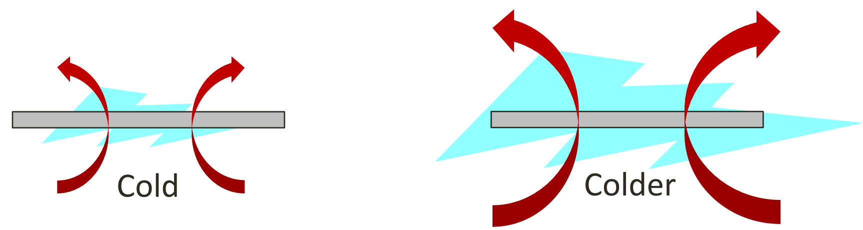
Study Objectives/Methods

EXAMPLE OBJECTIVE VECTOR

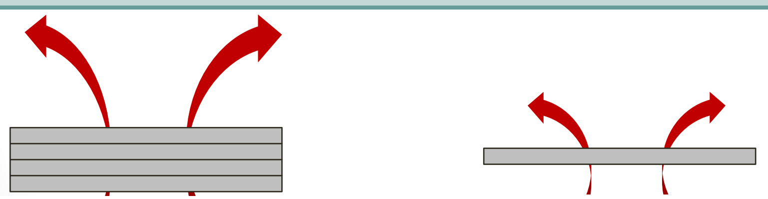
- **min**(total mass)
- **min**(power req'd)
- **min**(deployment time)
- **min**(thermal mass)
- **min**(mass/length or area)
- **min**(deployment steps)
- **max**(size ratio)
- **min**(current switching)

Thermal power draw ↓
Mag. field/mass ratio ↓

Thermal power draw ↑
Mag. field/mass ratio ↑



EXAMPLES



More turns in coil

Less turns in coil

Magnetic field ↑
Power/mass ratio ↓

Magnetic field ↓
Power/mass ratio ↑

SYSTEMS

Derive quantitative & qualitative impacts of HTS structures

Discuss architecture trade

Describe emergent capabilities

MISSION PRIORITIES

- Mission destination (LEO/GEO/Lagrange pt?)
- Need for reconfigurability
- Orbital parameters (Sun-sync? Eclipse time?)

TECHNOLOGY (HTSs VERSUS…)

- Inflatable structures
- Tensegrity structures
- Pyrotechnic fasteners
- Piezoelectric actuators or motors
- Spring-loaded booms and hinges
- Traditional motorized actuation

PERFORMANCE (WITHIN HTSs)

Study Objectives/Progress

Emergent capabilities:
Functions that are not feasible or not possible with other technologies

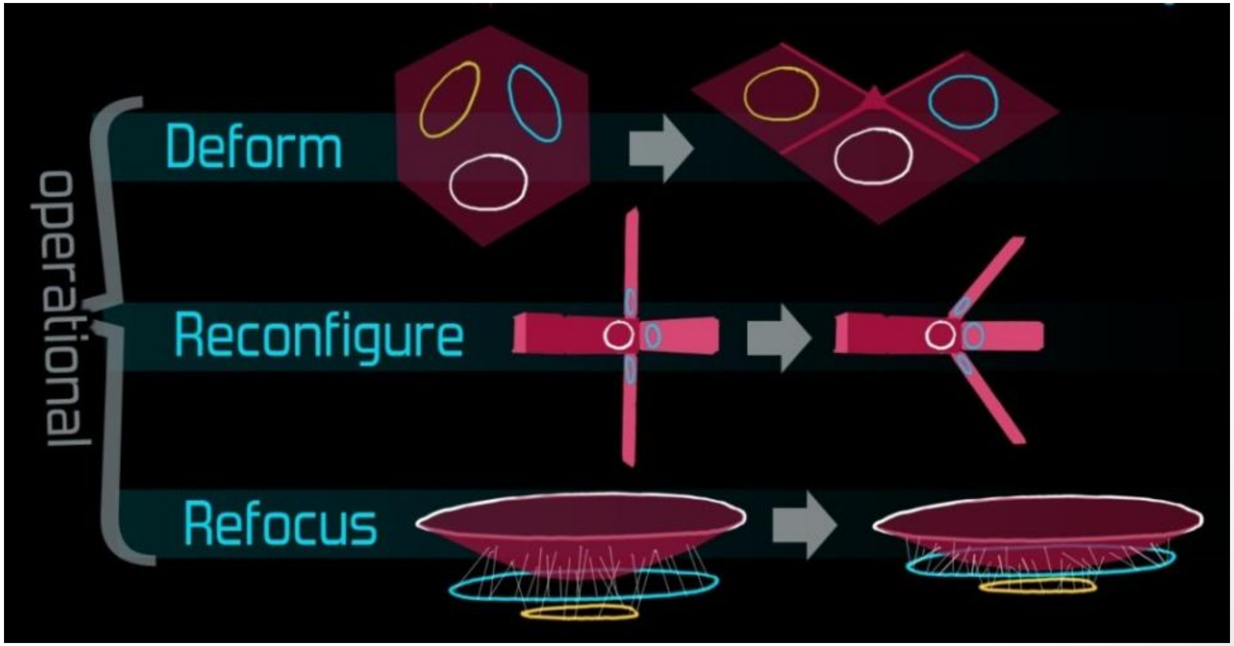
- Deforming/reconfiguring
- Refocusing (future)
- In-space assembly
- Staged deployment

SYSTEMS

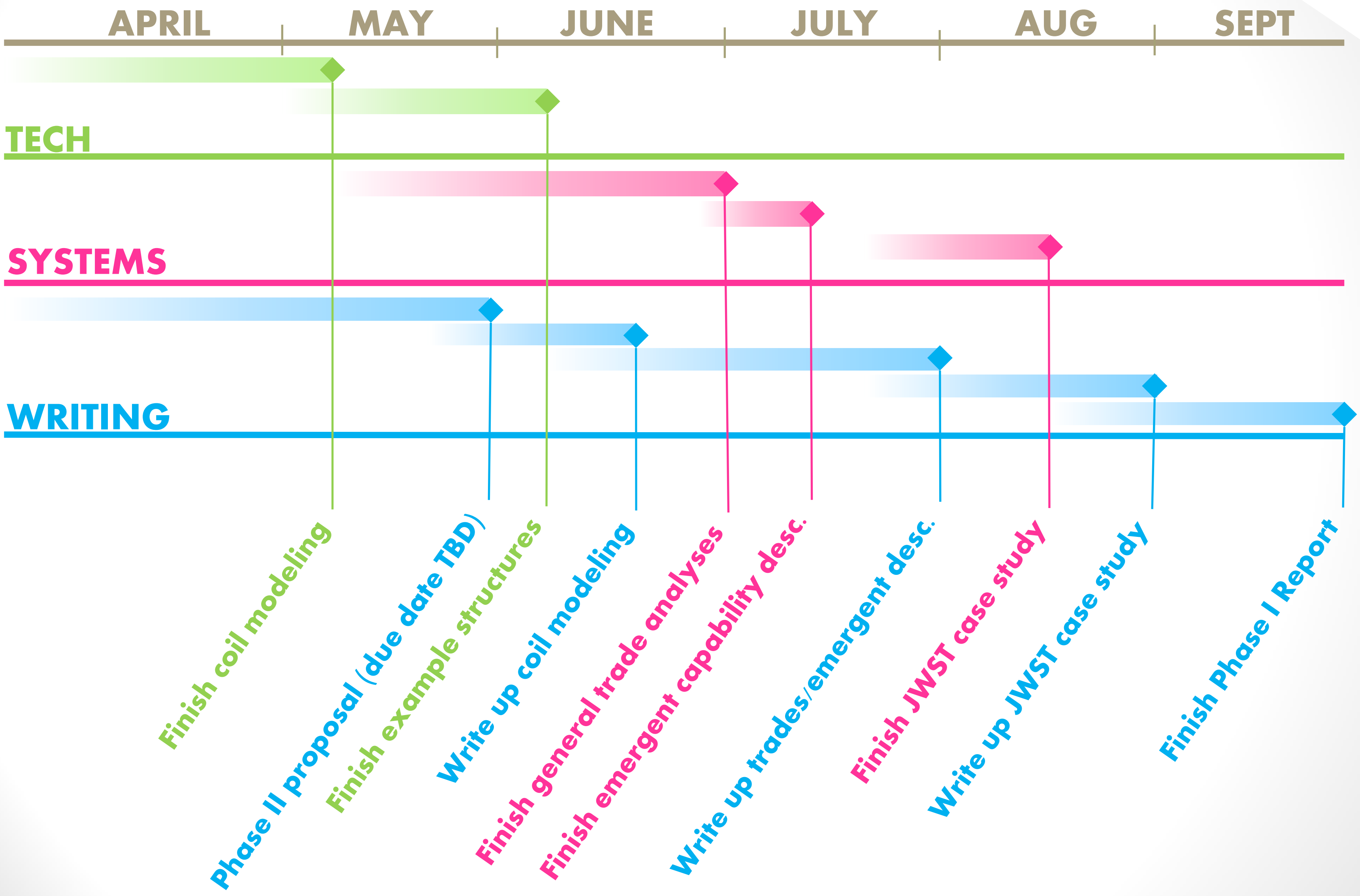
Derive quantitative & qualitative impacts of HTS structures

Discuss architecture trade

Describe emergent capabilities



Phase I Timeline



Final Remarks

TECHNOLOGY CURRENT STATUS:

- Mostly functional models of flexible single and double coil unconstrained systems
- Investigating validity of lack of oscillations in model
- *Next step: implementing constraints*

SYSTEMS CURRENT STATUS:

- High-level qualitative impacts and trades described
- More will emerge with quantitative analysis
- *Next step: quantify trades with completed coil models*

- Current progress consistent with hypothesis of feasibility
  - Breadth of applicability yet to be shown
- HTS structures not only present potential improvements over existing technologies, but enable previously infeasible functions
  - Staged deployment/in-space assembly and repair using EMFF
  - Isolation of sensitive payloads from vibration and heat

Final Remarks

Physically possible?	- Yes, fundamental physics support basic concept
Technologically achievable?	- Yes, but how broad will the applications be? - EMFF demonstrated
Economically reasonable?	- On par with other expensive and unique mission technology development - One goal is to make HTS technology generally applicable to reduce development costs across multiple programs
Desirable compared to other options?	- Planned research contribution

Questions?

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